Experiments with Piezo Ceramics (1)

physics and electronic components

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What do capacitors, electret microphones and passive infrared sensors have to do with one another? It is often interesting to go back to first principles and carry out a few experiments on the underlying phenomena. Electronics and physics belong together: and here we look at the physics behind some electronic components.

First, a simple experiment: take a ceramic capacitor and apply a high voltage. Now heat it briefly to 80 or 100 degrees Celsius, and let it cool slowly, keeping the voltage applied. The capacitor is now a completely new component with astonishing properties.

The voltage used must be on the limit of what the capacitor can stand: this will, depending on the capacitor, typically be anywhere from around 50 to over 500 V. Great care is required when using high voltages. **Figure 1** shows an isolated high-voltage supply, which allows a voltage in the desired range to be generated. Here a kind of adjustable transformer has been constructed from two transformers. A model railway transformer (without its rectifier) can also be used. A resistor limits the current to a safe value. The contacts must still nevertheless not be touched: and the voltage across the charged capacitor is not safe and can lead to painful skin burns.

A soldering iron can be used to heat the capacitor. It is sufficient to hold the heating element close under the capacitor. A few moments are

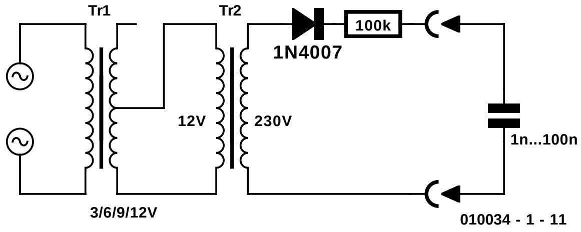

Figure 1. High voltage generator.

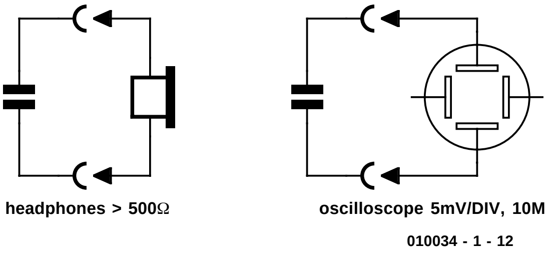

Figure 2. Testing the charge with headphones or an oscilloscope.

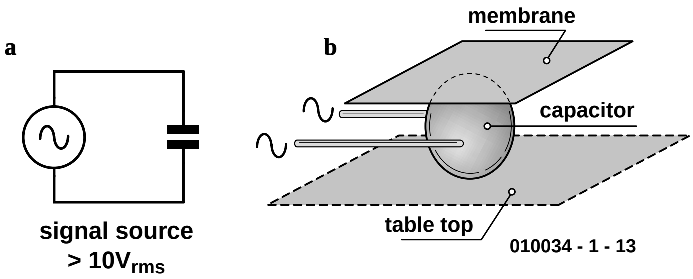

Figure 3. a. Use of the capacitor as an audio transducer.
b. Membrane arrangement.

enough, and then the capacitor can be left to cool.

A Phenomenon

After this special treatment the capacitor can be first shorted to discharge it. Then, high-impedance headphones can be used to check that it really is discharged fully. But now the interesting part: as soon as the capacitor is warmed in the fingers, it charges up a little. Connecting it to the most sensitive high-impedance headphones available, you can hear a quiet crackle. And then, when the capacitor is cooled, it charges again and you can hear it crackle again. This can be repeated as often as desired: each change in temperature leads to a small change in voltage.

Instead of headphones, an oscilloscope can be used to investigate this (**Figure 2**). With the test probes connected, a charge pulse of a few millivolts can be observed. On cooling, a pulse opposite in polarity to that seen on warming is observed.

Is this some innovative thermoelectric device or the long sought-after perpetual motion machine? Sadly not, because each change in temperature requires some energy. And a very small part of that energy is converted into electrical energy.

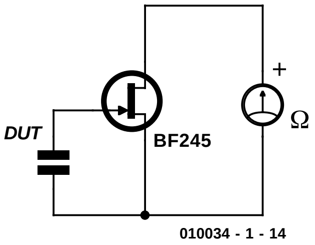

Figure 4. Static measurements with a FET.

There’s more

With the aid of the oscilloscope we can make a further interesting observation. The prepared capacitor charges itself and then discharges itself again when placed under mechanical force. The force must be applied very suddenly for any effect to be visible. It is clear, for example, if the handle of a screwdriver is used to hit the capacitor. Have we made our own microphone? In principle the answer is yes, although its quality is not exactly up to studio standards.

It might well be supposed that the effect is reversible, i.e. that the capacitor also acts as a loudspeaker. So, let us apply an alternating voltage (**Figure 3a**). We can use a tone generator operating at around 1000 Hz or the output of an amplifier. The signal voltage should be as high as possible. With 10 V_{rms} to 50 V_{rms} we can get satisfactory results. To make the sound audible, we need also a membrane to act as a diaphragm. For this we can use a piece of card or tin. The capacitor under test can be clamped between the membrane and a firm surface (**Figure 3b**).

Static forces

If the capacitor is connected to the input of an extremely high-impedance amplifier, we can also detect static forces. A constant pressure produces a voltage which remains present as long as the capacitor is not discharged. This can be shown very simply using an ohmmeter and a JFET (**Figure 4**). The FET alters its resistance as its gate voltage changes. The small changes can be measured very easily using a digital multimeter. Temperature changes can also be registered in this way.

When these possibilities have been exhausted, various types of ceramic capacitor can be tried: tubular capacitors, plate capacitors or multi-layer capacitors. The latter are available, for example, as surface-mount devices. The individual layers are so thin that they cannot stand very high voltages. If the maximum voltage is exceeded, then breakdown occurs and the capacitor is no longer usable. In other cases, only the outer case will be damaged. Capacitors mistreated in this way must of course not be used afterwards: it is better to experiment with old components from the junk box. It is in any case interesting to find out which types of capacitor make the best loudspeak-

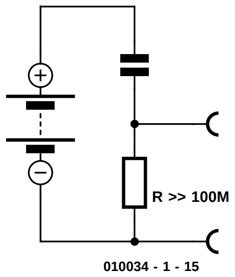

Figure 5. Principle of the condenser microphone.

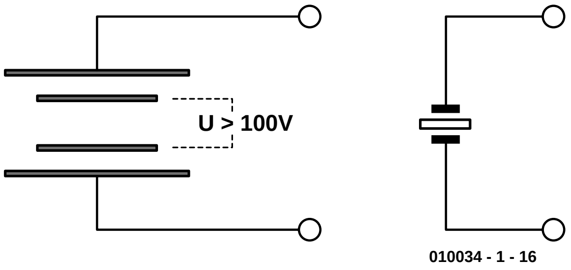

Figure 6. The internal charge of a polarised capacitor.

ers, microphones and pressure sensors.

Some physics

The capacitance, *C*, of a capacitor is equal to its charge, *Q*, divided by the voltage, *U*, across it.

$$C = Q / U$$

For example: a capacitor is charged for ten seconds with a constant current of 1 mA. The total electric charge is thus 10 mAs = 10 mC or 0.01 Coulomb. Fully charged, the voltage across the capacitor is measured at 10 V. The capacitance can now be determined:

$$C = 0.01\text{C} / 10\text{ V} = 0.001\text{ C/V} = 0.001\text{ F} = 1000\ \mu\text{F}$$

Our ceramic capacitors naturally have rather smaller capacitances, such as 100 nF. That means that with a given charging current they reach the final voltage so much quicker, and that the stored charge is correspondingly smaller.

As is well known, a capacitor (or "condenser" as it used to be called in the old days) can be constructed from two metal plates separated by a vacuum or layer of air. Its capacitance is given by:

$$C = \varepsilon_0 \cdot \frac{A}{d}$$

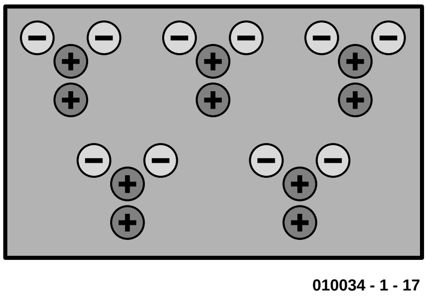

Figure 7. Model of a polarised dielectric.

where the **permittivity** of free space (or **electric constant**) ε_0 = 8.8542*10^{-12} F/m. The surface area *A* is measured in m^2, and the separation *d* in m. For a plate capacitor with an area A = 100 cm^2 = 0.01 m^2 and a separation d = 1 mm = 0.001 m this formula gives a capacitance of 88.5 pF.

The capacitance becomes smaller as the plate separation grows, and becomes larger as the plates are placed closer together. If the plate separation is increased on a charged and isolated capacitor, then the voltage across it increases. This may seem amazing, but it follows directly from rearranging the capacitance formula:

$$U = Q / C$$

The charge *Q* cannot change, because the connections are isolated. Hence the voltage must rise when the capacitance drops. This is the principle of operation of the condenser microphone in its basic form.

Capacitor = microphone

One of the two capacitor plates is the membrane. Mechanical movements are converted into electrical oscillations. For the microphone to work, the capacitor must be charged from a voltage source, typically of a few hundred volts. The microphone itself has a capacitance of only a few picofarads (**Figure 5**). The signal voltage must only be lightly loaded, and so a high-impedance connection is required. A high-impedance amplifier is best placed next to the microphone itself, and not at the end of a long cable.

Of course, the function of the condenser microphone is reversible. Electrical forces can thus be converted into movements of the membrane. This is the principle used in electrostatic loudspeakers.

When we compare our ceramic capacitor microphone with the condenser microphone we see only one difference: the lack of a voltage source. Or perhaps not: has something in our special treatment created some kind of battery? We must look at the whole thing as a capacitor within a capacitor, where the inner capacitor is permanently charged (**Figure 6**).

This process of charging the inner capacitor is called 'polarisation'. The charged material is now an 'electret'. There are various plastics and ceramics with which this can be done. Some materials, like quartz, already have this permanent electric field property without special treatment. A polarised capacitor, or electret system, can be represented with the circuit symbol for a quartz crystal.

Dielectric constants

Ceramic capacitors are frequently made from barium-titanate or similar ceramics. These materials have a particularly high dielectric constant. In comparison to an air-dielectric capacitor the capacitance can be as much as 10,000 times higher, i.e. ε_r = 10,000.

$$C = \varepsilon_0 \cdot \varepsilon_r \cdot \frac{A}{d}$$

Table 1 shows ε_r for certain important materials. Air, glass and epoxy resin all have relatively modest dielectric constants. But with water things are rather different, and its dielectric constant is conspicuously

Table 1

Dielectric constants for various substances

Substance	ε_r
Vacuum	1
Air	1.00059
Paper	2 - 2.5
Glass	2 - 12
Mica	4 - 8
Epoxy resin	3.6
Water	81
Ceramic substances	up to 10,000

high. What does water have that the others do not? Water is a polarized substance, meaning that the positive and negative charges in its molecules are not distributed in a uniform way. Each water molecule is a tiny charged capacitor. If they are aligned in an applied electric field, then together they create their own stronger field. Exactly the same thing happens, on a larger scale, in certain ceramic substances. When the internal charges are arranged at random, then the substance is not charged. This can be changed by the process of polarisation described above. The model of a polarised dielectric is shown in **Figure 7**.

Materials that can ‘store’ an electric field in this way are called **ferroelectric**. The idea is to indicate a comparison with the magnetic properties of iron. Iron contains magnetic dipoles whose orientation can be affected by an external magnetic field. If the magnetisation is strong enough, the internal field can be partly retained. **Remanence** (or residual magnetism) is a typical characteristic of iron and steel. Particularly good magnets can be made by magnetising the material at high temperature and then cooling it: exactly the same happens with ferroelectric materials in an electric field. The parallel goes further: each material has its own characteristic temperature beyond which the stored field is lost: this is called the **Curie point**. A piece of iron made to glow red will certainly lose its magnetisation.

The Curie point of the commonly used barium-titanate ceramics is around 55 °C. It must therefore be possible to return our polarised capacitor to its original condition. So, warm it briefly with a soldering iron (or even in hot coffee), and it soon will no longer work as a loudspeaker. If necessary, it can be used as if it were new.

Ferroelectric ceramics can in principle be polarised without the use of heat. For some materials it suffices to apply a high enough voltage to create the electret. The effect is not particularly distinctive with commonly available ceramic capacitors: hence our use of heat and applied voltage for best results.

The processes going on in the dielectric are relatively complicated. Sometimes the special properties are only noticeable in a limited temperature range. Ceramic capacitors with high values generally also have high temperature coefficients. Looking in more detail, we see that the capacitance has a maximum value at a certain temperature, which is not necessarily room temperature. Put simply, the capacitance changes with changes in temperature. The internal charge, however, remains constant. Hence the voltage across the capacitor must change, and exactly this effect was observed at the start of this article. Any temperature change changes the external charge on the capacitor.

In the case of an air-dielectric capacitor the plate separation must be halved to change the voltage across the capacitor by 50%. For a polarised ceramic capacitor, a change of rather less than 1 % in dielectric thickness has a similar effect. In such a hard material, this naturally has to do with the large forces that are at work. Inside the material charged crystal lattices shift against one another, leading to large changes in the electric field. At this level the effect operates differently. When a voltage is applied the material distorts as a result of the electrical forces. The possible movements are not great, but the forces are considerable. A ceramic loudspeaker does not have a great travel, but a relatively large diaphragm can be moved.

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In the second and final part of this article we focus on technical applications of piezo ceramics.

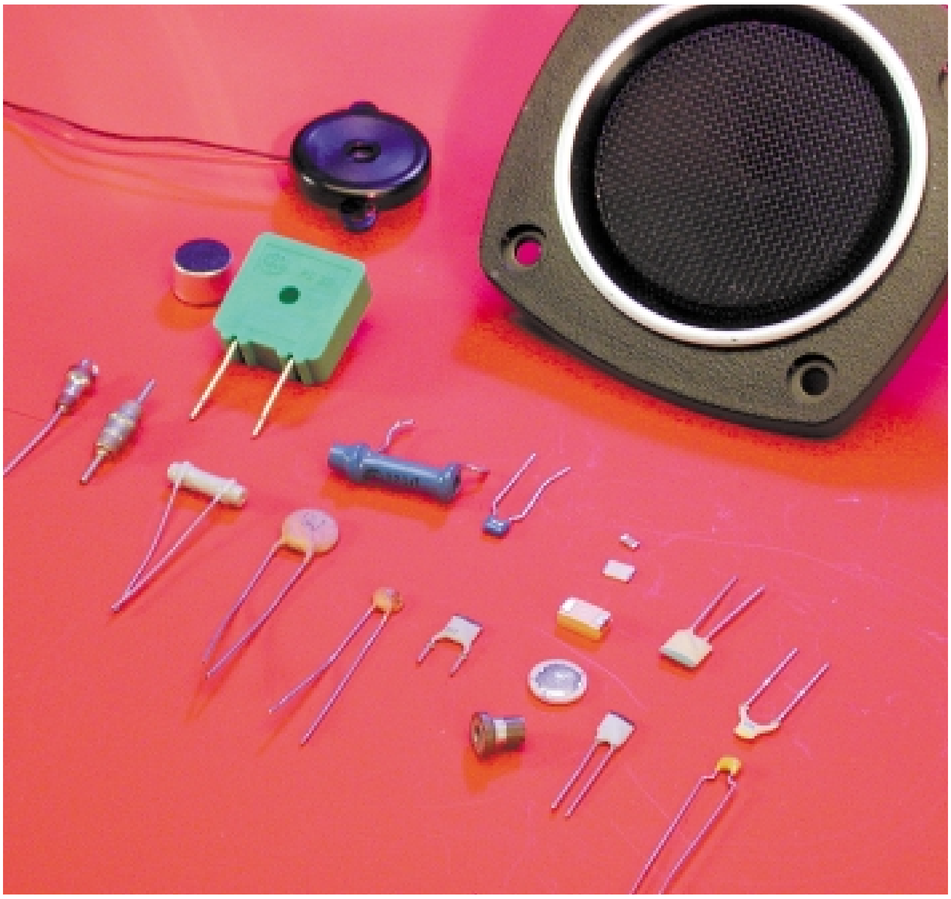

Figure 8. Some electronic components made from ceramic substances. The front row shows a selection of RF capacitors.